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HYDRAULIC STUDIES OF NOISE AND VIBRATION IN A TWO-WAY, OPEN-TOP DROP INLET SPILLWAY

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AGRICULTURAL RESEARCH SERVICE • U.S. DEPARTMENT OF AGRICULTURE

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HYDRAULIC STUDIES OF NOISE AND VIBRATION IN A TWO-WAY, OPEN-TOP DROP INLET SPILLWAY[1]

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INTRODUCTION

The principal spillway for the Soil Conservation Service (SCS) floodwater reservoir at Site 8 on Upper Clear Boggy Creek near Stonewall, Okla., (fig. 1) was reported to have vibrated during a flow event.

A storm inspection report by Forrest McClung (SCS area engineer) contains the following statement concerning the vibration:

> General remarks: Mr. Foreman, landowner, expressed concern about the vibrating caused by the principal spillway when the pipe flow changes from full flow to partial flow.

A detailed description of the occurrence is given in the following quotation from page 2 of a trip report from Horace M. Haws (head, SCS Oklahoma Design Section) to William T. Burtschi (then SCS State conservation engineer) dated October 17, 1967:

> In regard to the vibration, Mr. Foreman stated that as the pool emptied from an elevation 8 inches above the inlet splitter wall to the elevation of the splitter wall that a recurring loud 'clap' was audible at his home approximately one-half mile from the structure. This was accompanied by a sucking noise and slugging and surging of the outflow. Considerable vibration of the embankment was reported during this period of slug flow. Unlike a single structure that would empty through a comparable stage in perhaps hours, this series structure with inflow from the upstream structures requires several days to pass through this stage. Due to the length of time involved it is felt that further study of this inlet design is warranted. Mr. Foreman reported that a single vortex located downstream from the splitter wall was evident during this period of slug or surging flow.

The reported vibration was of concern to the SCS engineers who have the responsibility for designing adequate and safe hydraulic structures. In this instance, it is possible that the vibration may have become noticeable only because of relatively long flow duration in a critical range. If the flow had been in the critical range for a very short time, the vibration might have escaped notice. Long duration flows are possible at the drop inlet spillway at Site 8 because the Site 8 reservoir receives the outflow from six upstream reservoirs. The storm of September 4 and 5, 1967, was probably distributed so as to produce a prolonged outflow and the reported vibration and noise phenomenon. Because this phenomenon could happen again, the SCS engineers sought a solution to the problem of eliminating or reducing it.

An appeal was made by SCS to the Agricultural Research Service, Water Conservation Structures Laboratory, at Stillwater, Okla., for help in solving this problem. A model study of the drop inlet spillway was conducted to explore the vibration and noise phenomenon, and to seek a solution. This paper describes our attempt to duplicate the reported flow behavior of the prototype in the model drop inlet. A solution is offered for reducing the only significant noise that occurred in the model.

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[1] Contribution from the Soil and Water Conservation Research Division, Agricultural Research Service, U.S. Department of Agriculture, in cooperation with the Oklahoma Agricultural Experiment Station, Stillwater.

[2] Research hydraulic engineers, Soil and Water Conservation Research Division, ARS, Stillwater, Okla. Mr. Hebaus is now a civil engineer with the Corps of Engineers, Department of the Army, St. Paul, Minn.

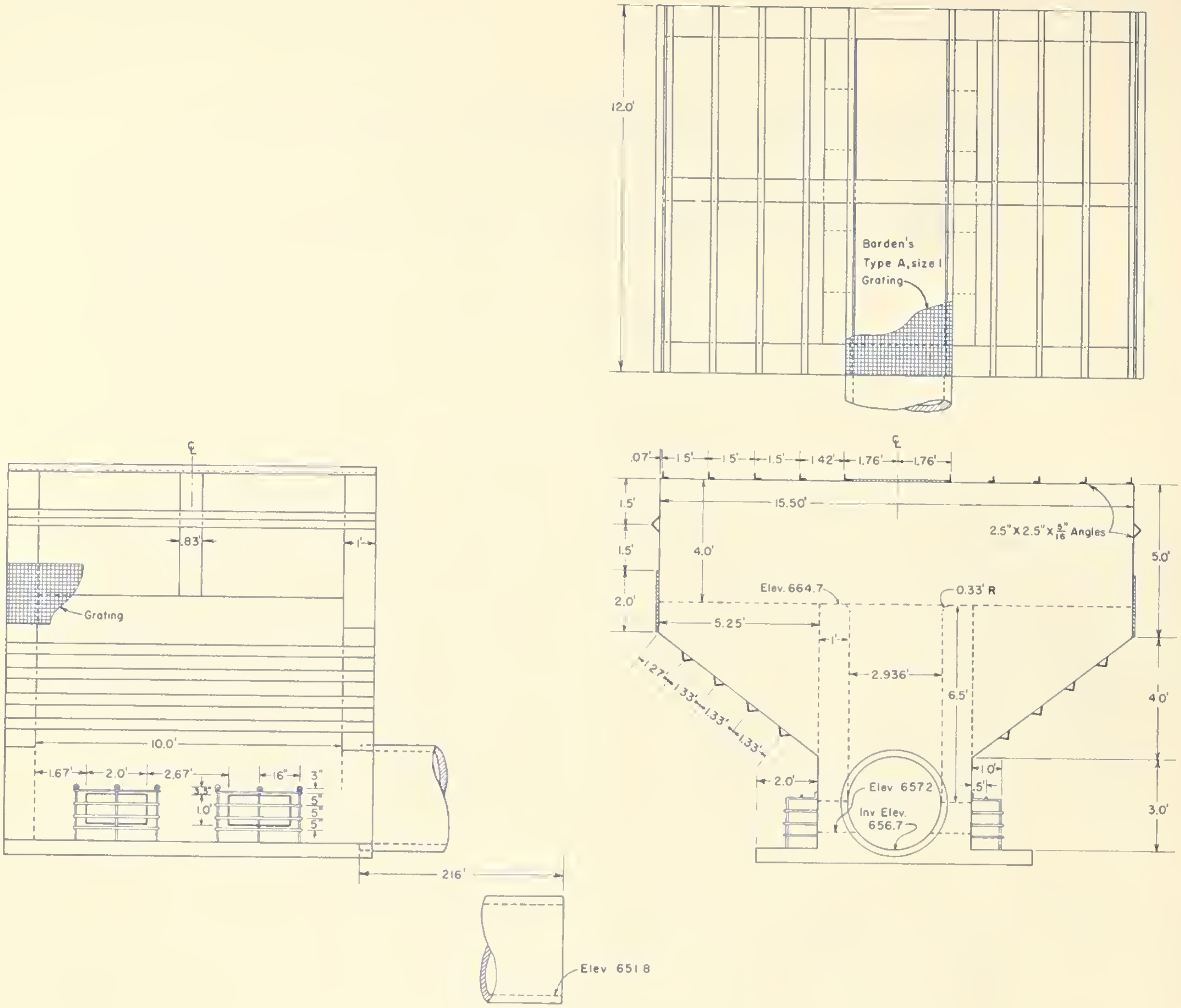

Figure 1.—Two-way drop inlet for Upper Clear Boggy Site No. 8.

PROTOTYPE DESIGN

The prototype two-way drop inlet (fig. 1) contains four 1- by 2-foot drain ports. These are symmetrically located on the sides near the inlet's bottom. The bottom of the drop inlet is semicircular and has the same radius as the pipe. The top half of the pipe entrance is square edged. The top of the drop inlet is open and has a splitter wall as an antivortex device.

The head-discharge relationship for the pipe flow range of the prototype was computed by using the friction coefficients described by Straub, Bowers, and Pilch[3] for 36-inch cast concrete pipe with good joints, and a total entrance loss coefficient K_e of 0.59 obtained from preliminary tests of the model.

MODEL DESIGN

A model of the prototype drop inlet was installed and tested in the closed conduit model basin (fig. 2) at the Water Conservation Structures Laboratory. The inside diameter (D) of the pipe used for the model was 3 inches. The corresponding dimension of the pipe used for the prototype was 36 inches. Therefore, the model-prototype length scale ratio was 1:12. Entrance conditions and vortex formation were of primary

[3] Straub, L.G., Bowers, C.E., and Pilch, M. Resistance to flow in two types of concrete pipe. Univ. of Minn., St. Anthony Falls Hydraulic Laboratory, Tech. Paper No. 22, Ser. B, 148 pp., illus. 1960.

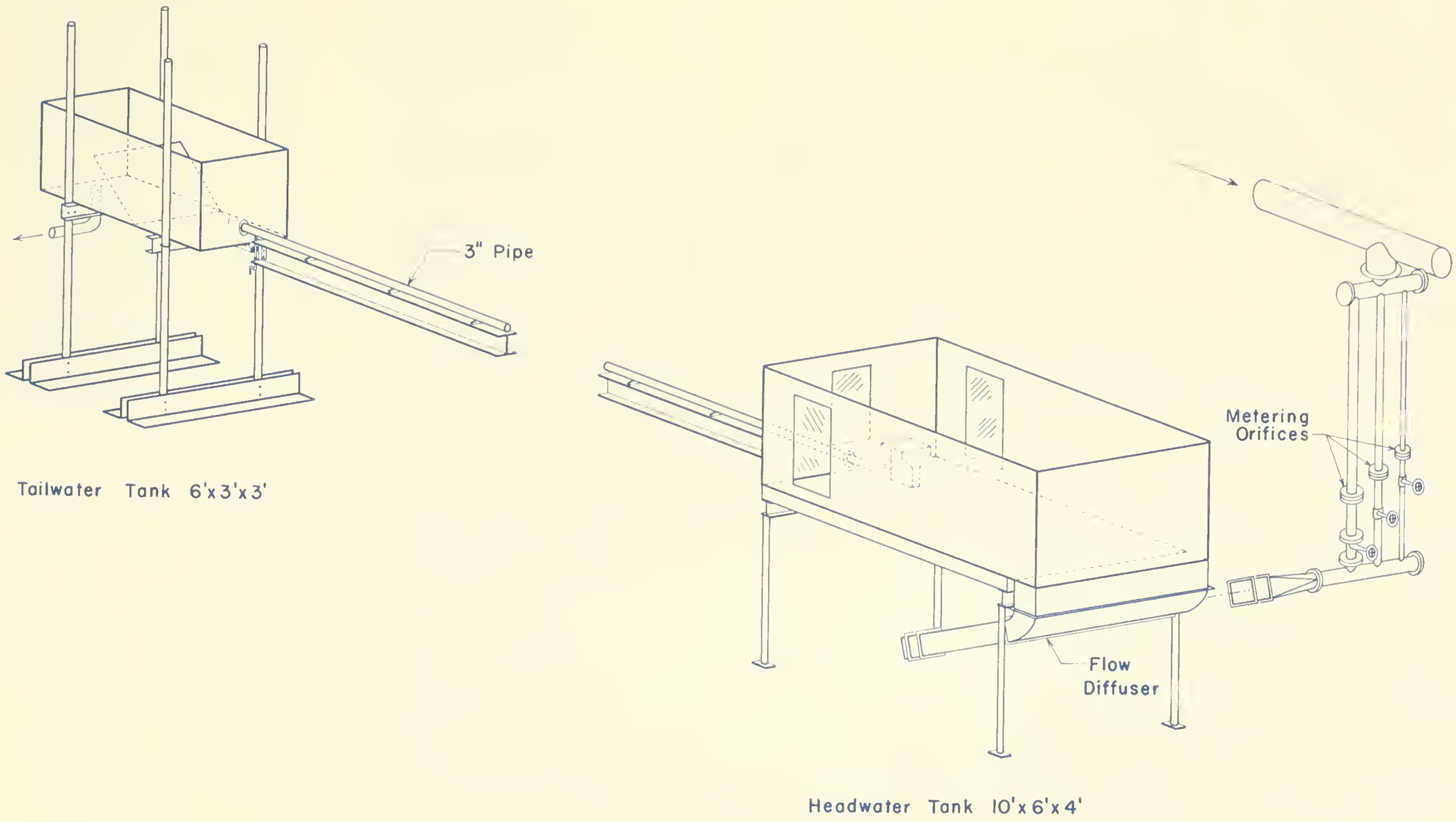

Figure 2.—Closed conduit model basin.

interest. Because these factors are controlled by the forces of gravity on a free water surface, similarity of model and prototype was based on the Froude model law. Model-prototype relationships were as follows:

Property	*Model scale*
Length	1:12
Area	1:144
Velocity	1:3.464
Discharge	1:498.8

The pipe used in the model was made of clear Plexiglas. Friction coefficients for this pipe approximate those for "smooth pipe" curve in the turbulent flow region. The friction coefficients for the model, however, were relatively greater than those of the prototype because of the model's smaller Reynolds' number. In the model, therefore, the pipe was placed on a steeper slope than that of the prototype to simulate the discharge of the prototype. Exact simulation of the prototype discharge is possible for only one discharge rate in the pipe control range. The discharge selected for simulation occurs when the headpool water level is 8 inches above the splitter wall and the pipe has free discharge.

The model of the drop inlet was built to scale except for the aluminum deck grating located on the top and sides of the prototype. This grating was simulated with hardware cloth having approximately the same percentage of open area as the grating. In the model, the topography around the prototype was molded with a thin layer of cement over a compacted sand bed (fig. 3).

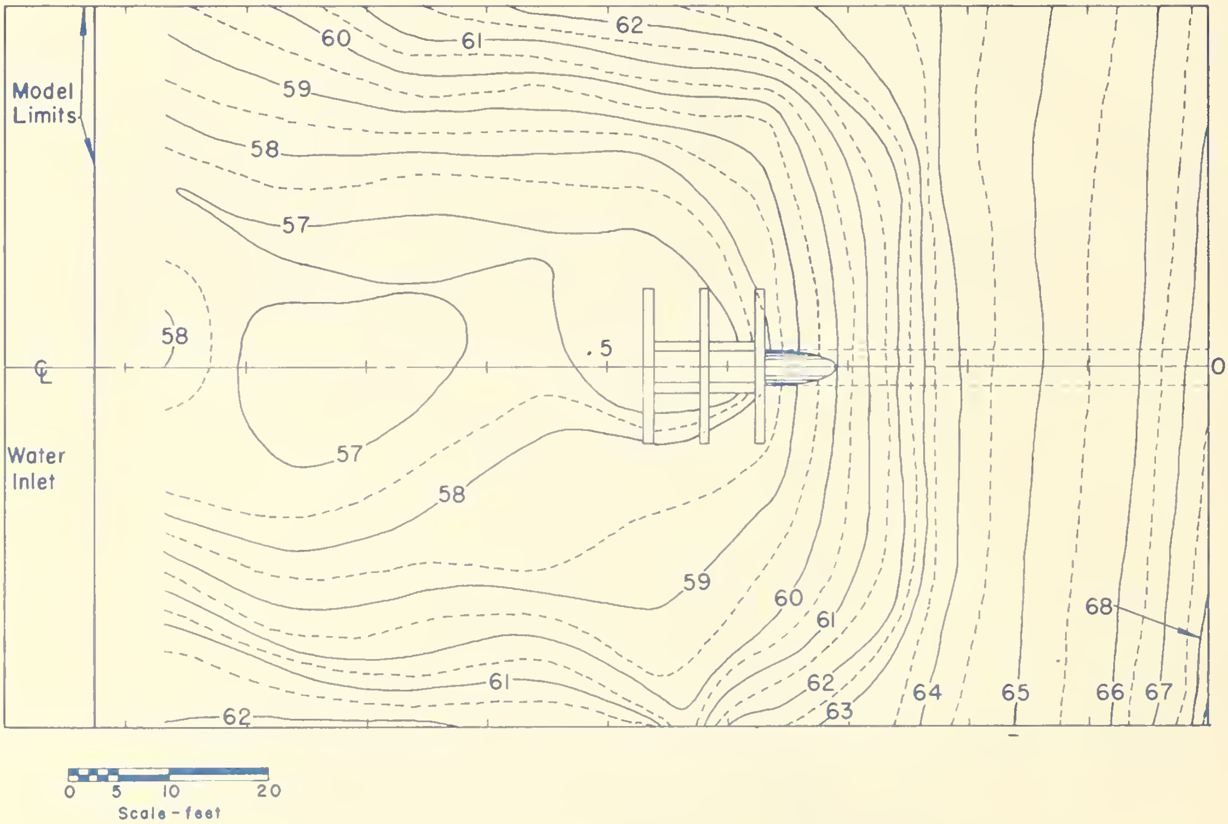

Figure 3.—Model layout and topography of Upper Clear Boggy Site 8. (Note: Add 600 to each contour to obtain elevation.)

MODEL TESTS AND RESULTS

The model drop inlet was tested first to verify and observe the vibration and noise phenomenon reported in the prototype. Various methods for eliminating or minimizing noise in the model were tried. Hydraulic coefficients were determined for each test. Sound generated in the model was recorded on ¼-inch tape and 16-mm. movies were taken for the eight tests included in figure 4.

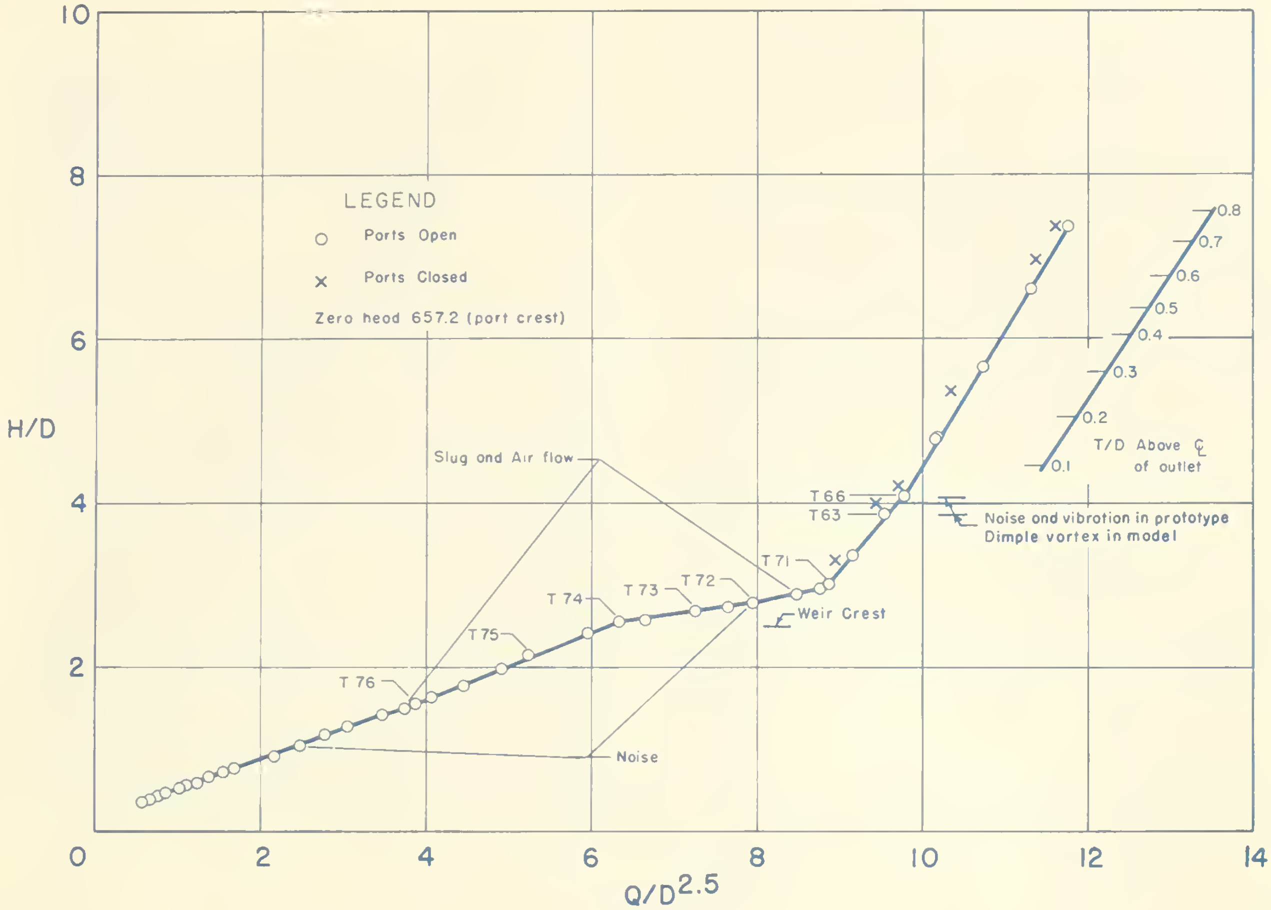

Figure 4.—Head-discharge relationship for Upper Clear Boggy Site 8 model.

The head-discharge relationship for the drop inlet spillway is controlled by three types of flow: orifice flow through the four ports, a combination of orifice flow through the ports and weir flow over the crest, and pipe flow through the spillway. Figure 4 shows the results of the tests on the model and how these three types of flow influence the head-discharge relationship. The head (H) is referenced to the crest of the ports, elevation 657.2 feet. D is the diameter of the pipe, and Q is the discharge.

MODEL TESTS FOR FLOW CONTROL

Control by Ports

In the headwater range between the ports and the drop inlet crest, the flow was governed by orifice control at the ports. As the flow increased, noise created by air feeding through the pipe began at an H/D value of 1.0 (pool elevation 660.2 feet). Whenever this head was reached during the tests the opposing jets from the ports "piled up" turbulent water above the pipe entrance and sealed it. When this sealing occurred, the pipe momentarily primed and drew the water level in the drop inlet down to the pipe crown elevation. Air then entered the pipe and broke the prime. This cyclic action of sealing, priming, and breaking prime persisted through the orifice flow range. Thus, the effective head on the orifice was the difference in elevation between the water surface in the reservoir and the pipe crown at the entrance. Orifice coefficients for the ports were computed using this head in the equation:

$$C = \frac{Q}{A\sqrt{2g\,\Delta H}} \qquad (1)$$

where
- C = orifice coefficient
- Q = discharge (c.f.s.)
- A = total area of ports (ft.^{2})
- g = gravitational constant (ft./sec.^{2})
- ΔH = headwater pool elevation minus pipe crown elevation of 659.7 feet

Computed orifice coefficient values are plotted versus corresponding values of ΔH in figure 5. The average

value (fig. 5) for C, obtained by using equation 1, was 0.65. This value is in agreement with orifice coefficients for rectangular orifices suppressed at bottom only.[4]

Control by Orifice and Weir

Weir flow over the drop inlet crest began at an H/D value of 2.5 (elevation 664.7 feet). The control was then a combination of orifice control through the ports and weir control over the drop inlet crest. Orifice and weir control was maintained in the headpool range between the drop inlet crest (pool elevation 664.7 feet, H/D = 2.5) and a point 1.3 feet above it (pool elevation 666 feet, H/D = 2.93). During most of the orifice and weir control range, the turbulent flow in the drop inlet and the slug flow associated with incipient priming produced considerable noise. This phenomenon continued until the headpool reached a level 1.1 feet above the drop inlet crest (H/D = 2.87, fig. 4). No noise was noted in the model when the headwater exceeded this level. As the control changed from the orifice and weir to pipe control, the opposing weir nappes produced an oscillation of the water surface within the drop inlet.

[4] King, H.W. Handbook of hydraulics. Ed. 4, rev. by E.F. Brater. 563 pp., illus. New York. 1954.

Control by Pipe

Pipe control began at elevation 666 feet (H/D = 2.87). As the flow increased and the water level rose above this elevation, careful attention was given to the flow behavior in the model. Of particular interest was the range in which the loud clap occurred in the prototype (H/D range from 3.83 to 4.06). No such noise occurred during the model pipe control tests. However, the intensity of circulation over the downstream half of the drop inlet increased in this flow range. During each test, except for the one with the largest discharge, a small dimple formed and dissipated over the downstream half of the drop inlet. Whenever the top grating was removed from the model, a vortex with a long, slender air core formed in this area. However, very little, if any, air was transported through the pipe.

The failure of the model to duplicate reported prototype behavior in the 3.83 to 4.06 H/D flow range was disappointing. We reasoned that circulation in the prototype reservoir might possibly enhance vortex formation. To test this idea, we blocked off one-half of the approach to the model to introduce flow asymmetry in the basin and rotation around the test structure. However, this change did not increase vortex activity. With or without the asymmetry in the approach flow, circulation in the form of a dimple-type

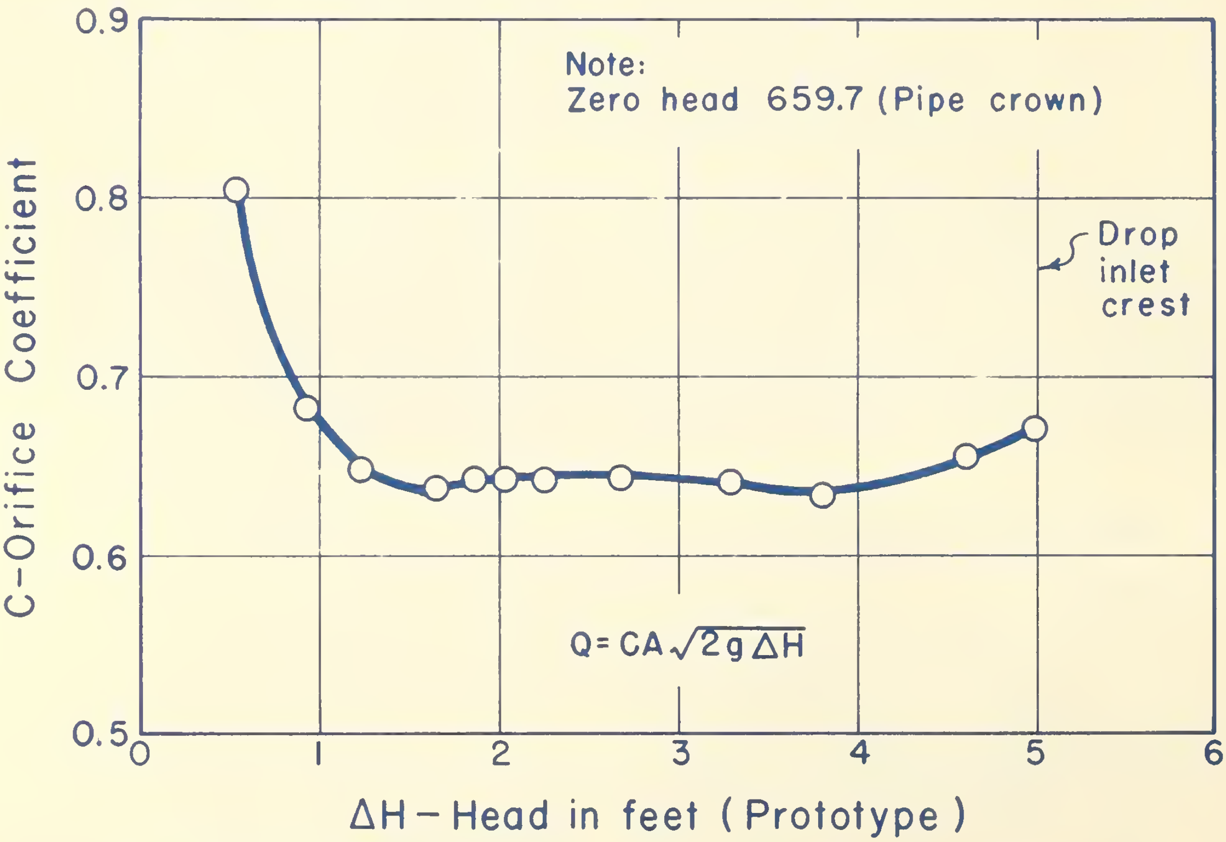

Figure 5.—Orifice flow through four low water ports of Upper Clear Boggy Site 8 model. (See equation (1).)

vortex was noted for flows with headpool levels above the splitter wall, but neither noise nor vibration were noted in this range. From these observations, we concluded that if a vortex is observed in the model, one is likely to occur in the prototype, and that the vortex may be more violent in the prototype than in the model.

The elevation of the outlet end of the closed conduit on the model had been set so that at an H/D value of 4.06, and with free outfall, the model discharge would equal the estimated prototype discharge. Above this H/D value the model discharges were slightly less than the estimated prototype discharge with free outfall. The estimated prototype head-discharge curve could be made to coincide with the model curve by assuming higher tailwater levels in the prototype. Tailwater elevations required to bring the estimated prototype discharge down to the values obtained in the model tests were calculated. These tailwater depths are expressed in dimensionless form and plotted on figure 4 (zero tailwater depth assumed to be at the centerline of the outlet pipe at the downstream end). For example, at H/D of 6, the value of $Q/D^{2.5}$ for the model is approximately 11, whereas for the prototype to have the same discharge at this H/D value, a tailwater depth equal to 0.4D is needed.

MODIFICATIONS TO MINIMIZE SLUG FLOW

The noise in the model occurred in the air and slug flow range which extended from H/D = 2.85 down to H/D = 1.5. McClung's report states that vibrating occurred when the pipe flow changed from full flow to partial flow. Model tests showed that change from pipe control to weir control occurred at H/D = 3. Thus, the model tests tended to confirm McClung's report and to indicate that there was a noise problem in the slug flow range. Haws' report indicates that as the pool emptied, a loud noise began at H/D = 4.06. This level is well above that at which slug flow begins. Yet, Haws' report mentions slugging and surging of the flow. Thus, even though the model did not duplicate the loud noise, it appeared to duplicate the noise in the slug flow range. Therefore, model studies were continued to determine practical ways to eliminate sucking and slurping sounds associated with slug flow.

Closing Two Downstream Ports

Water entering the drop inlet through opposing ports tended to pile up and seal the pipe entrance. Whenever this occurred during an individual test, the pipe momentarily primed and then broke prime because the flow through the ports could not maintain full pipe flow. The cyclic action of prime and break contributed to the slugging and surging of the flow. We concluded that closing the two ports nearest the pipe entrance would probably reduce water pile-up at the entrance and thereby eliminate some of the surging of the flow. The two downstream ports were closed to test this theory. When these ports were closed, slug and air flow occurred over the same discharge range as that recorded when all four ports were open. (Compare figs. 6 and 4.) However, the range in head for a slug flow with the two ports closed was less than that with the four ports open. Thus, the length of time flow in the slug flow range was reduced with the two ports closed. However, the time required to empty the pool was increased.

Providing Round Air Vent

The next attempt to eliminate or reduce slug and air flow was to provide an air vent to the atmosphere to prevent incipient priming of the pipe. Tests of shaft spillways reported by Mussali and Carstens[5] showed that ventilating the upstream end of a conduit delayed sealing and provided short tube control. Therefore, ventilation was tried in the model to prevent incipient priming. The simplest way to provide the vent in the field would be to use available pipe and fasten it on the inside on the drop inlet. This procedure would require setting the top of the pipe at an elevation that would provide venting throughout the slug flow range. This arrangement was simulated in the model, as shown in figure 7, and the test results are shown in figure 8. The installation of the vent destroyed the single valued head-discharge relationships for the spillway. Destruction of these relationships makes it impossible to predict the discharge rate for the drop inlet spillway because the discharge rate for a given head would depend on previous flow history. However, this defect is not considered to be an important problem in installations where the capacity of the spillway is very low relative to emergency spillway capacity. The slug and air flow range was reduced slightly, but not enough to indicate that the round vent offered any particular advantage in preventing incipient priming.

Providing Rectangular Air Vent

For these tests, the round pipe used as an air vent in the previous test series was replaced with a rectangular vent with the bottom cut to the radius of the barrel crown. The dimensions of this vent and its positioning in the drop inlet are shown in figure 9. The top of the vent was set 1 foot lower than the weir crest so that the weir flow would submerge the vent opening when the discharge was sufficient to maintain orifice flow at

[5] Mussali, Y.G., and Carstens, M.R. A study of flow conditions in shaft spillways. Georgia Institute of Technology, Atlanta, WRC-0669, 158 pp., illus. 1969.

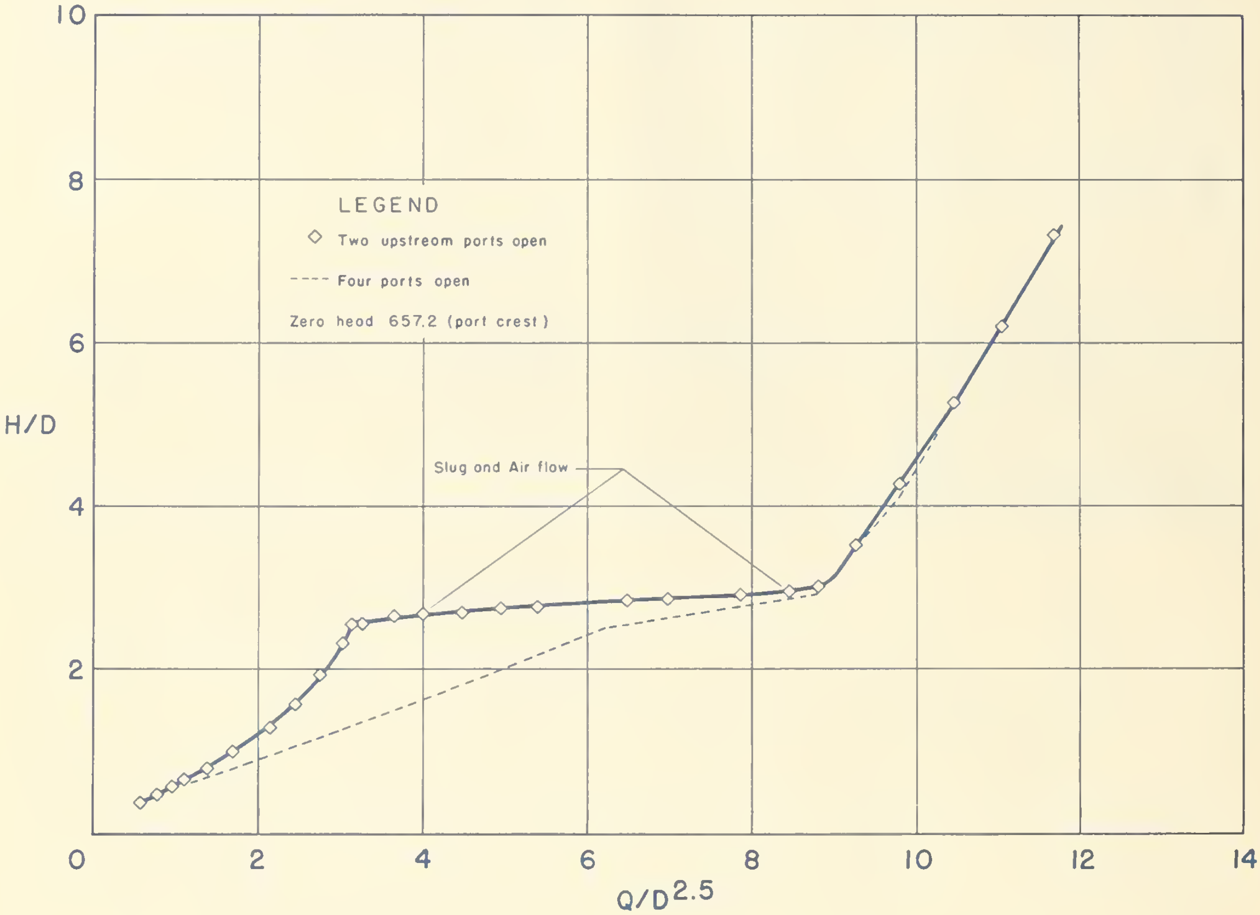

Figure 6.—Head-discharge relationship for Upper Clear Boggy Site No. 8 model, modified by closing the two downstream ports.

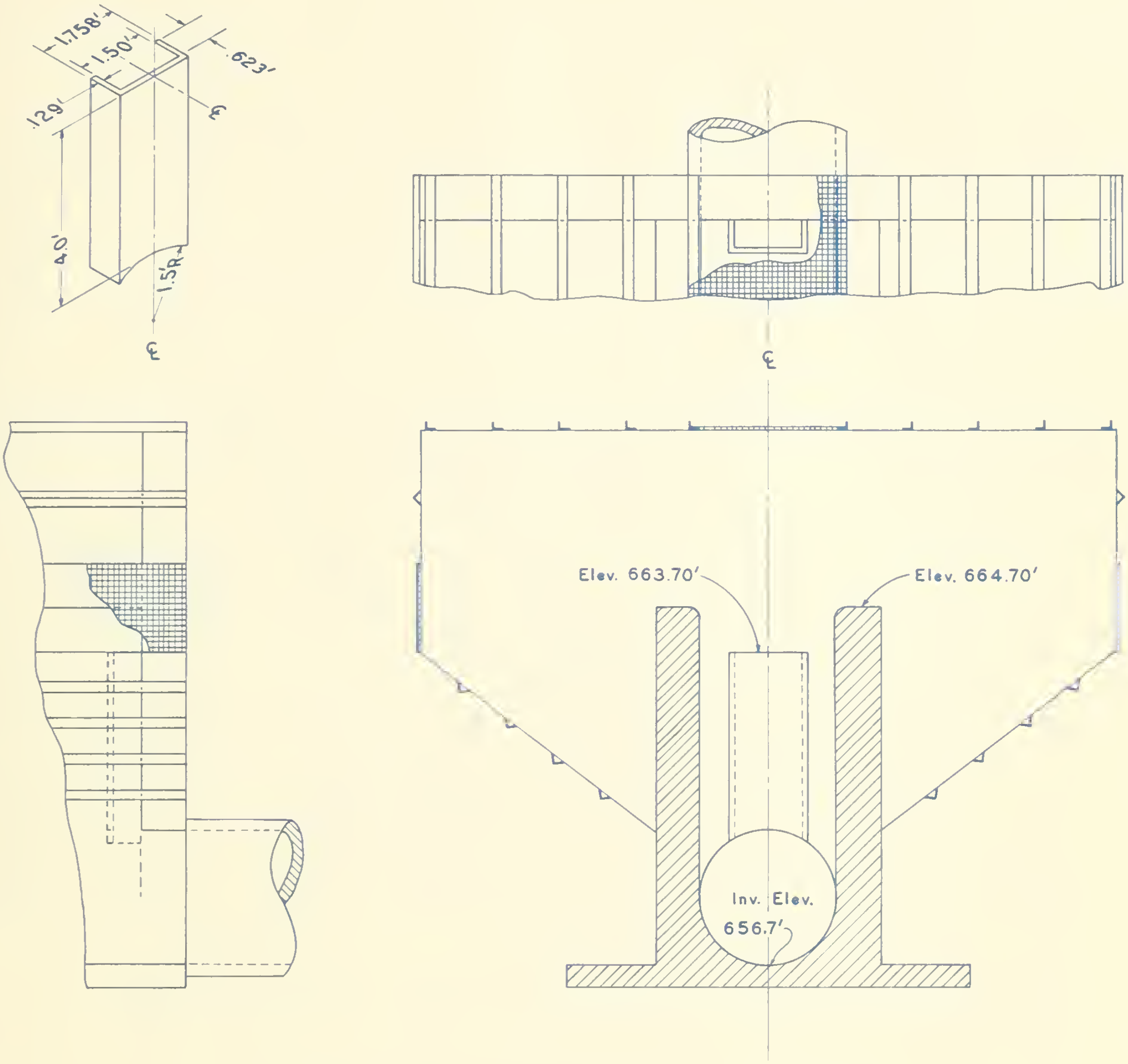

Figure 7.—Round vent modification to Upper Clear Boggy Site 8 model.

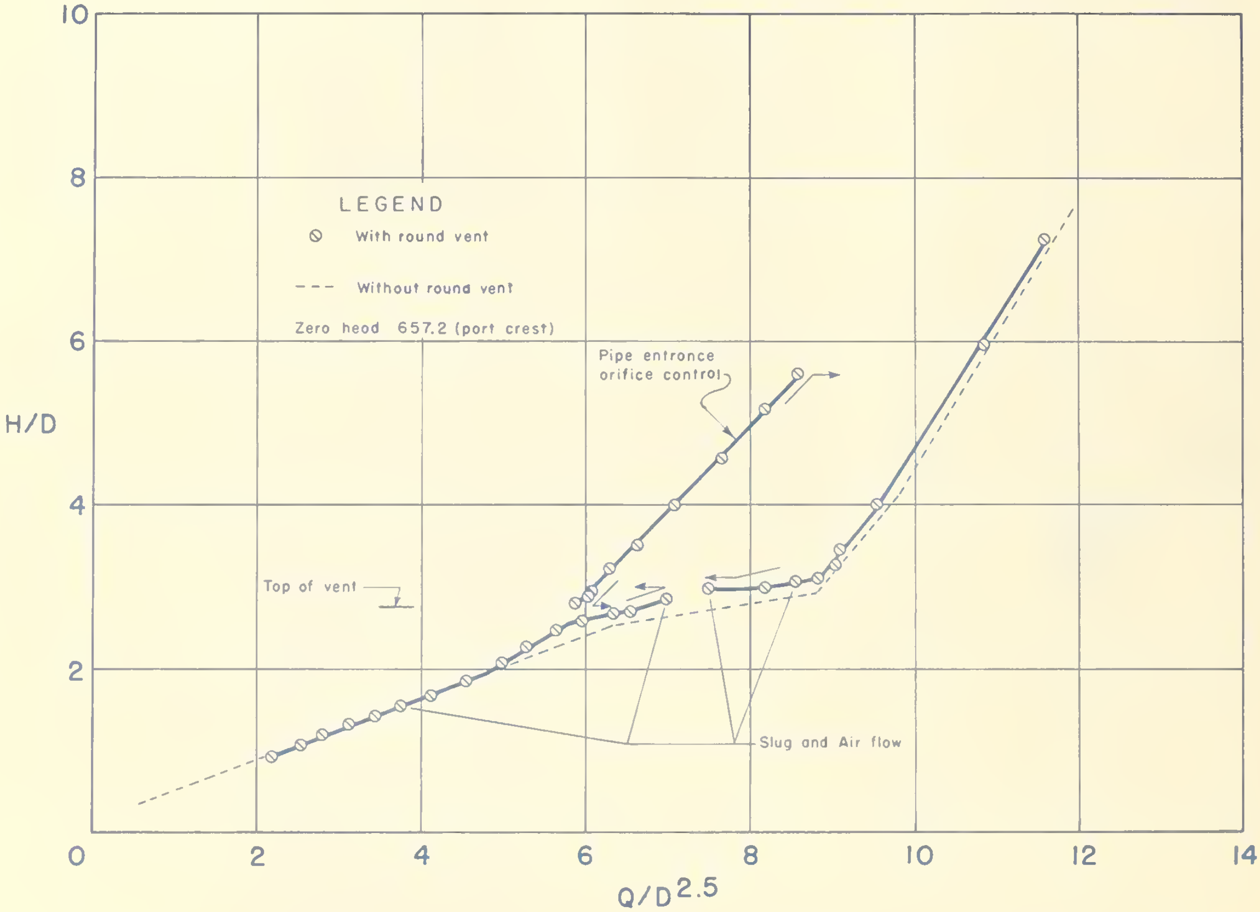

Figure 8.—Head-discharge relationships for Upper Clear Boggy Site 8 model, modified with a round vent pipe.

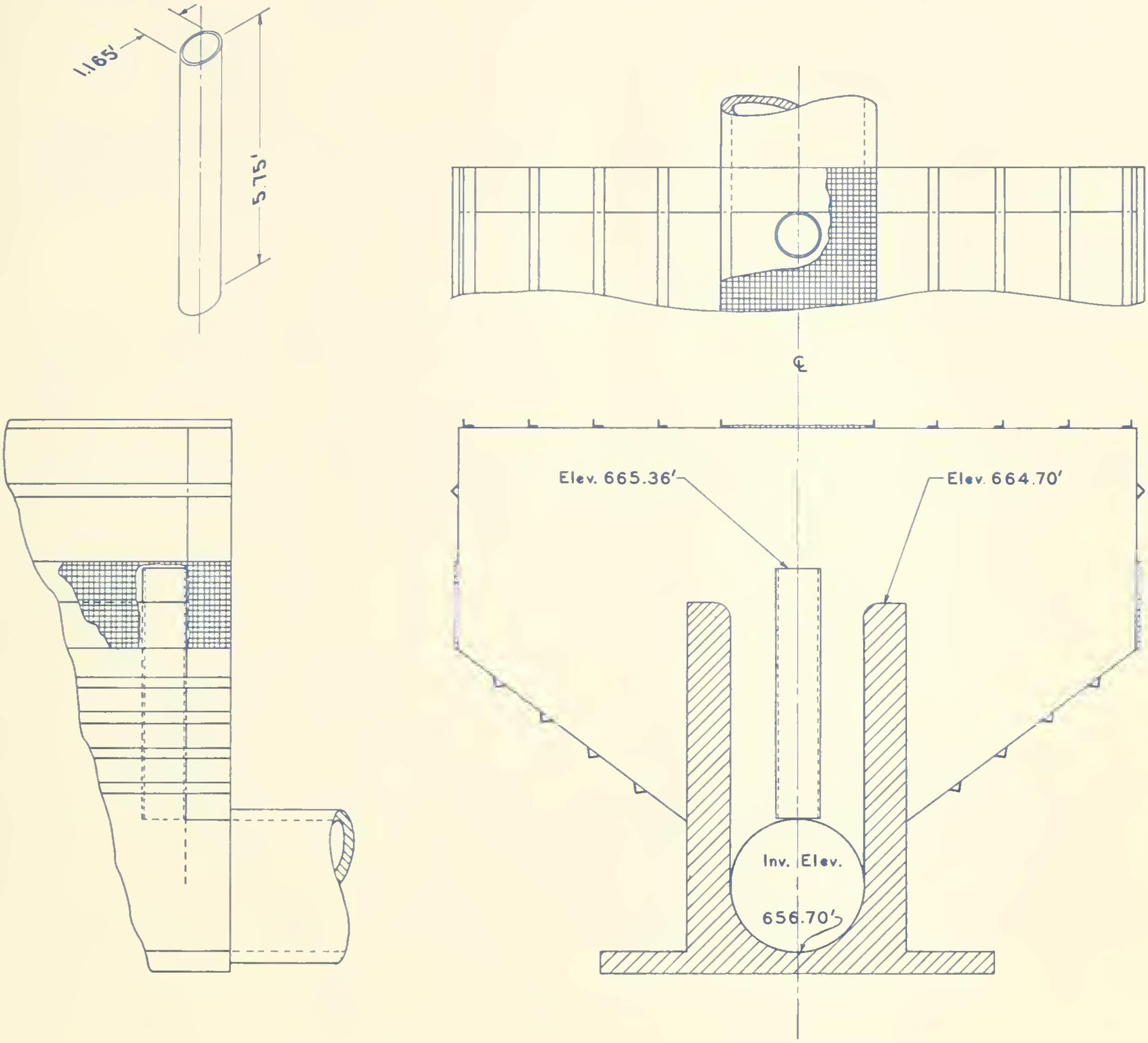

Figure 9.—Rectangular vent modification to Upper Clear Boggy Site 8 model.

the pipe entrance. The circular shape and square edge of the bottom of the rectangular vent caused the upper surface of the jet to contract whenever it entered the pipe. As a result of the separation of the water from the crown of the pipe, atmospheric pressure was maintained at the entrance to the pipe through the vent and incipient priming was prevented. Thus, whenever the water level built up in the drop inlet above the pipe crown, this level was not drawn back down to the pipe crown level, as it had been when a vent was not in place. At these times, the differential head on the ports for a given pool level was less with a vent than without one. This decrease is reflected in the lower $Q/D^{2.5}$ values shown in figure 10 for H/D values less than 2.5. In this range, air was feeding through the rectangular vent; however, no slug flow occurred. This air flow persisted through the short orifice-weir combination control range. Very little noise, however, was associated with the air feeding.

As the discharge was increased above the short orifice-weir control range, the water inside the drop inlet sealed the entrance to the rectangular vent. The control then shifted to the pipe entrance and stayed in this mode during the rising flow until H/D reached 5.7. At this stage, flow control shifted abruptly to pipe control. The values of $Q/D^{2.5}$ for the model in the pipe flow range are lower with than without the vent for like values of H/D because of the increased entrance loss caused by the vent. No air intake or noise occurred during the pipe entrance control or the pipe control flow stages.

When the discharge rate was decreased from the preceding high rate, the flow remained in pipe control until orifice-weir control began, without reverting to barrel entrance control. Slug and air flow then started and existed for a short range as the discharge was decreased further. Some noise was generated in this range.

HYDRAULIC COEFFICIENTS

Because hydraulic coefficients measured during the tests may be useful to design engineers, they are presented with observations of the model performance.

Crest Loss Coefficients

The pipe flow crest loss coefficient K_c is defined by the equation

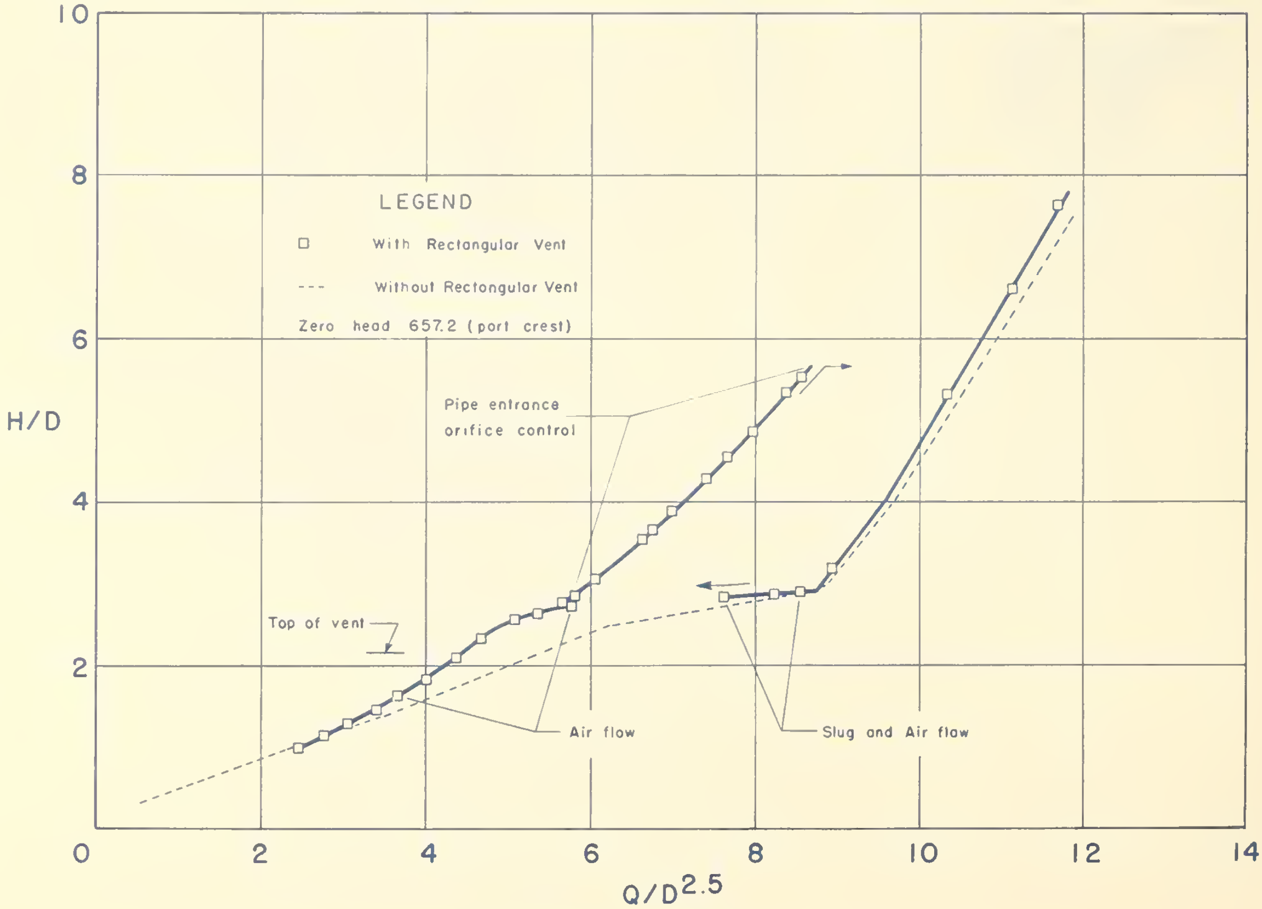

Figure 10.—Head-discharge relationship for Upper Clear Boggy Site 8 model, modified with a rectangular vent.

$$K_c = \frac{H_c}{\frac{V_r^2}{2g}} \qquad (2)$$

where H_c = head loss at the crest of the drop inlet and through the trash rack (ft.)
V_r = average velocity in the riser (ft./sec.)
g = gravitational constant (ft./sec.^{2})

K_c reflects head losses at the crest and also through the trash rack but does not include head losses at the pipe entrance. Six piezometers located at the midheight of the drop inlet—one each on the upstream and downstream end walls, and two on each sidewall at the third points—were used to measure the head loss. Thus, each piezometer was assumed to represent the average pressure in one-sixth of the drop inlet cross section. Because of nonuniform velocity distribution in the drop inlet cross section, the observed pressure drop was different at each piezometer. The pressure differences were attributed to velocity head differences because H_c was assumed to be the same at each piezometer. The best value for H_c was found by an iterative calculation which required that H_c be equal at each point and that the sum of the six incremental area-velocity products equals the total measured discharge.

The four ports were closed while K_c was determined. This procedure was necessary so that the total discharge in the riser at the measuring cross section could be measured. Closing the ports reduced the capacity of the model (compare the crosses and open circles in fig. 4) in the pipe flow range by a small amount. K_c decreased as the head increased (fig. 11). This effect is typical of open-top drop inlets where the approach flow paths to the inlet change with pool elevation.

Entrance Loss Coefficients

The pipe flow entrance loss coefficient K_e is defined by the equation

$$K_e = \frac{\Delta h_e - \frac{V^2}{2g}}{\frac{V^2}{2g}} \qquad (3)$$

where Δh_e = difference in elevation between the headpool surface and the pipe hydraulic grade line projected to the entrance (ft.)
V = average velocity in the pipe (ft./sec.)
g = gravitational constant (ft./sec.^{2})

Six pressure measurements along the pipe were fitted by the method of least squares to a straight line to obtain the hydraulic grade line. These pressure measurements were recorded from equally spaced manifold sections located in the downstream portion of the pipe.

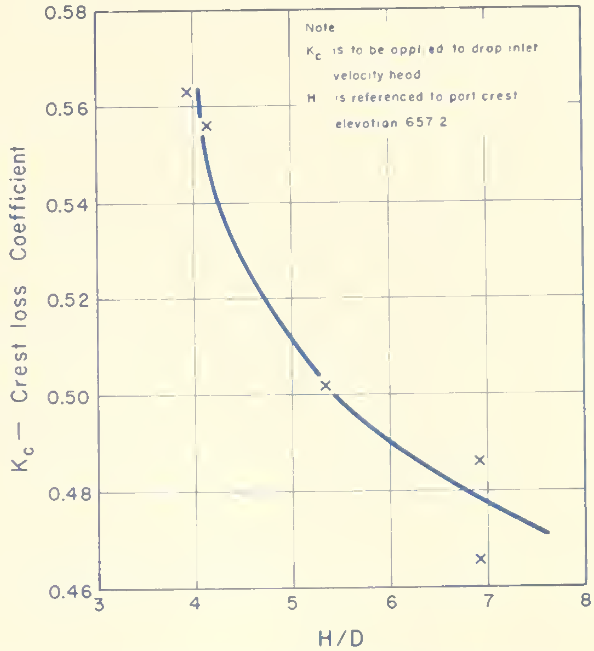

Figure 11.—Crest loss coefficients for Upper Clear Boggy Site 8 model, with four ports closed.

The values of K_e were measured in all tests. The results are presented in figure 12.

Pipe Entrance Orifice Coefficients

With a vent in place, either circular or rectangular, flows occurred for which the pipe flowed only partly full, yet the weir was submerged. The pipe entrance was then exerting the primary control on the pool level by acting as an orifice. The range of heads for these flows was approximately 7.4 feet to 15.6 feet. Orifice coefficients for the pipe entrance for this range were calculated by the equation

$$C_0 = \frac{Q}{A\sqrt{2g\,H_0}} \qquad (4)$$

where C_0 = pipe entrance orifice coefficient
Q = discharge (c.f.s.)
A = cross-sectional area of barrel (ft.^{2})
g = gravitational constant (ft./sec.^{2})
H_0 = headwater pool elevation minus elevation of center of pipe entrance (ft.)

The coefficients are plotted versus head on figure 13. The coefficient values are approximately the same with either the round or rectangular vent in place. The crest losses and friction losses in the drop inlet were disregarded when the orifice coefficient was calculated.

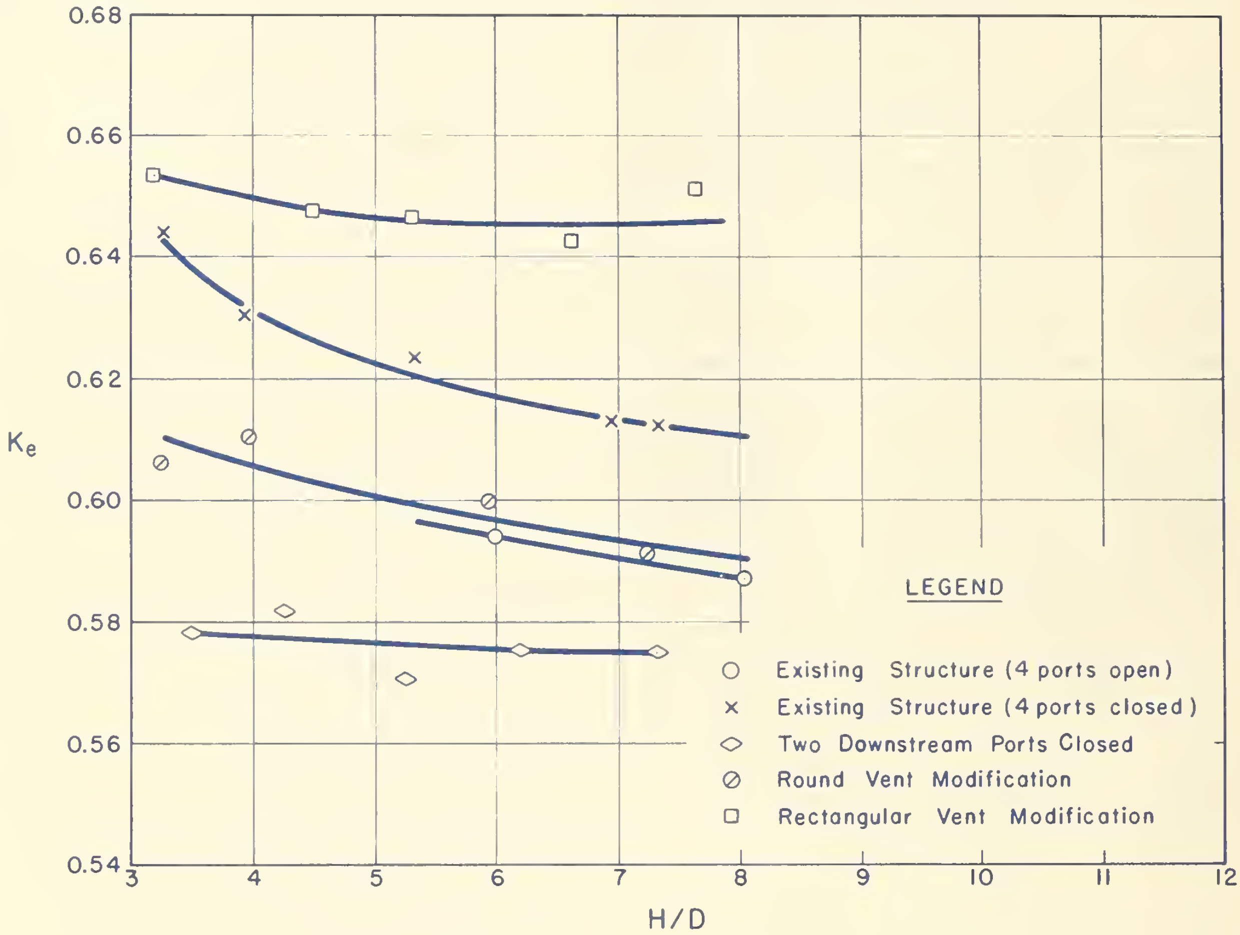

Figure 12.—Entrance loss coefficients for Upper Clear Boggy Site 8 model.

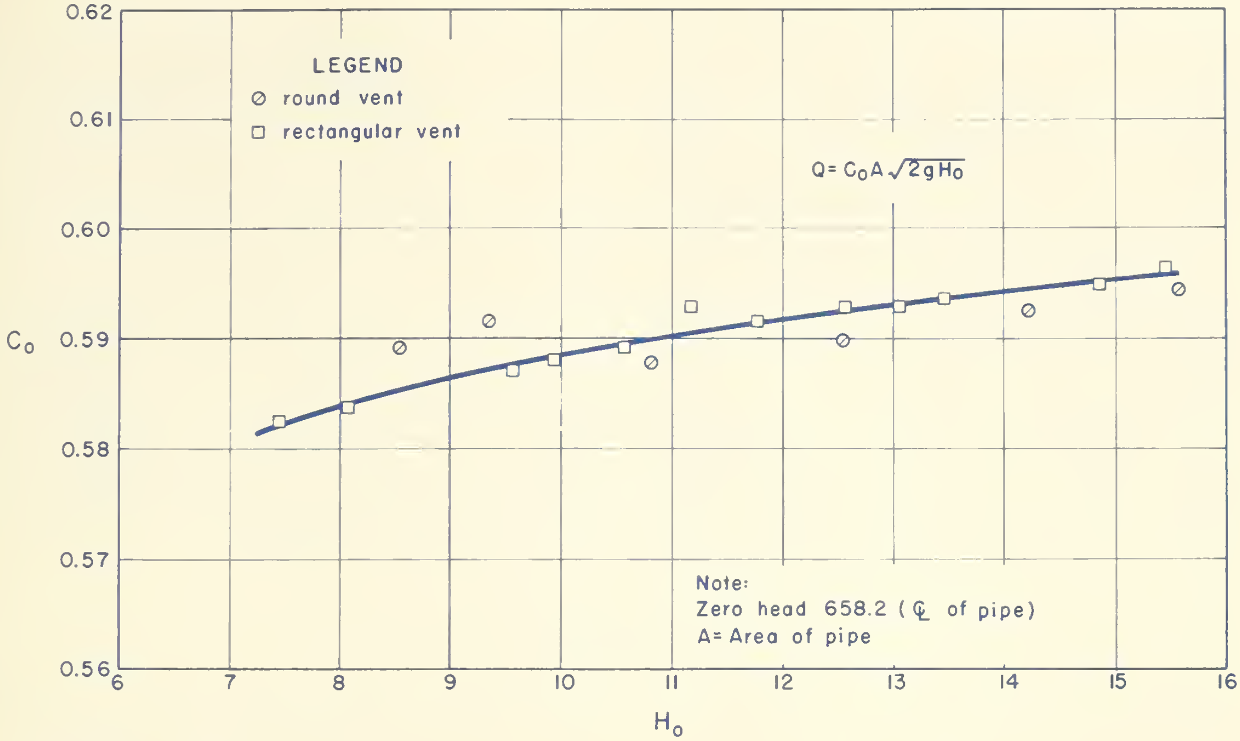

Figure 13.—Pipe entrance orifice coefficients for the short-tube flow range of Upper Clear Boggy Site 8 model, modified with vents at the entrance to the barrel.

FIELD OBSERVATIONS

On October 8 and 9, 1970, the region around and including Site 8 experienced a heavy rainfall. Surrounding towns of Ada, Coalgate, and Sulphur, Okla., reported totals of 6.94, 9.25, and 12.62 inches of rain, respectively, for these dates. This event filled the reservoir to the level of the emergency spillway crest (10.1 feet above the splitter wall, H/D = 7.2) and provided an excellent opportunity to observe the prototype spillway in action.

As in previous flow events, a massive trash load was brought in with the flow. Trash was abundant because this reservoir had not been cleared during construction. The trash consisted mostly of rigid, floating members, covering a wide range of shapes and sizes. The largest member was about 15 inches in diameter and 20 feet long. Some of the trash was distributed along the shoreline, but most was left on the face of the dam. On October 20, 1970, when the site was observed with the pool level 5 feet above the splitter wall (H/D = 5.5, fig. 4), some trash was circulating over the inlet, but this trash had blown away by midafternoon.

On October 23, with the pool level 3.5 feet above the splitter wall (H/D = 5.0), a small vortex was noted above the drop inlet. However, there was no noise or air flow through the core. Vortex activity at this level would probably have been less if the transverse splitter wall had been located differently. Donnelly[6] found that the most effective location for a transverse antivortex wall was at a point about one-third of the drop inlet length from the downstream end. The midpoint location used in this drop inlet is not recommended.

Unfortunately, we were not at the site when the pool reached the level at which the loud noise was expected. The landowner reported that he did not hear any noise as the headpool dropped through the stage near the top of the splitter wall on October 26. On October 27, with the pool level 1.25 feet below the top of the splitter wall (H/D = 3.42) and the structure in pipe flow, varying sizes of vortices were forming on each side of the splitter wall. No noise, vibration, or air entrainment was occurring at this time. The vortices in the prototype were larger than those noted in the model. A few sticks and other types of trash were lodged on the grating over the drop inlet.

[6] Donnelly, C.A. Tests of an antivortex wall for a rectangular drop inlet to a closed conduit spillway. U.S. Dept. Agr. ARS 41-96, 8 pp., illus. 1964.

On October 28, the pool water surface was just above the weir crest and the structure was flowing in slug flow. Slugs were transmitted at varying frequencies, ranging from 12-second to 2-minute cycles. The cantilevered outlet pipe did not vibrate and very little noise was connected with the slug flow. One log, 3 inches in diameter and about 5 feet long, had passed through the trash rack and was caught on the weir crest of the downstream half of the drop inlet. The opposing jets of the ports created considerable turbulence, air entrainment, and fluctuating water surface within the drop inlet for flows controlled by the ports.

The outlet pipe was more than half submerged in the tailwater for all flows observed. This submergence may have affected the spillway's performance and may be one explanation of why it performed differently with respect to noise for this event than for the earlier one. However, this explanation is speculative because the tailwater level for the earlier event is unknown.

Another explanation for the differences in noise generation for the two events could be difference in the amount of trash accumulated on the top grating. Some trash lodged on the grating during the observed event and could have reduced the intensity of vortices. Inasmuch as the amount of trash accumulation on the top grating during the earlier noisy event is unknown, this explanation, too, is conjectural. However, the model tests indicated that if the top grating is removed, vortex intensity can be increased. So it is reasonable to assume that the vortex intensity can be affected by the amount of trash on the top grating. Therefore, if noise generation depends on vortex formation, this explanation is a plausible one. It in turn suggests that one solution to a noise problem would be to replace the top grating with a solid plate.

SUMMARY

Hydraulic model studies were conducted to investigate the noisy operation and vibration of a closed conduit spillway for a floodwater retarding reservoir and to find ways to eliminate these conditions. The loudest noises were reported to have occurred when the flow was in the lower stages of pipe control and to have been accompanied by slugging and surging of the outflow. The model did not perform in a corresponding manner. A small vortex developed in the model in the critical range, but this effect was the only flow disturbance observed in this range.

Loud sucking noises did develop in the model with the onset of weir flow following pipe control flow. The addition of a vent that admitted air directly to the pipe entrance stopped incipient priming of the pipe and greatly reduced noise. However, with the vent in place the model spillway no longer had a unique head-discharge relationship. This lack of uniqueness may, in some cases, be an acceptable alternate to a unique rating and noisy operation.

Soon after the model studies were completed, a major flood occurred that caused the prototype spillway to flow at near-maximum capacity. Observation of the prototype during this event indicated that it performed much like the model, except that vortices were larger than those in the model. The prototype spillway did not generate noise during this event. Two explanations are advanced for the apparent change in the noise generation characteristics of the spillway. The submergence of the outlet could have been different for the two events, or differences in the amount of trash accumulated on the top grating could have affected vortex formation and noise generation.

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